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Theoretical investigation of heat-flux spreading in metal-clad ridge-waveguide diode lasers*

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Results of the theoretical analysis of heat spreading in metal-clad ridge-waveguide (MCRW) (InGa)(AsP)/InP laser diodes are presented in this work. In a typical MCRW laser diode the abstraction of heat through the ridge appears to play only supplementary role in the whole heat-sinking process, since 60%–70% of the heat flux generated in the active region of this laser flows through the substrate. Theoretical values of the thermal resistances of a typical MCRW laser diode ($S = 5$ μm) are equal to 59 K/W and 68 K/W for the copper and the silicon submounts, respectively. These values agree very well with the experimental data.

1. Introduction

Metal-clad ridge-waveguide (InGa) (AsP)/InP laser diodes [1]–[8] are ones of the most promising coherent light sources in fibre optical communications because of their excellent operation characteristics as well as of their low-cost, one-step LPE manufacturing.

Operation characteristics of these diodes are, however, distinctly temperature-dependent. Therefore it seems advisable to investigate their thermal model and compare the obtained results with the experimental data.

2. Theoretical model

The analysis of heat-flux spreading in the metal-clad ridge-waveguide (MCRW) (InGa) (AsP)/InP laser (Fig. 1) is rather complex because of its "ridge" construction (usually with two channels), multilayer structure and non-homogeneous boundary conditions. The last feature is due to the fact that most of the upper surface part of the laser is covered with an oxide layer, whose thermal conductivity is relatively low, while the vertical walls of the ridge are or are not covered with such a layer. Both cases have been considered, but the calculated thermal resistances do not differ distinctly.

It is rather impossible to find an exact analytical solution to this complex heat spreading problem. Numerical methods are much time-consuming, require a very

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quick and capacious computer and are efficient only when using special numerical procedures not always available. Therefore, the analog electrical method of the calculations has been chosen.

The main heat source in the laser is placed in its active layer and is connected mostly with nonradiative recombination and, to a lesser degree, with the absorption of radiation within and near this area. We assume that the active layer heat source, because of its undoubtedly dominant role, is the only heat source in the RW laser diode.

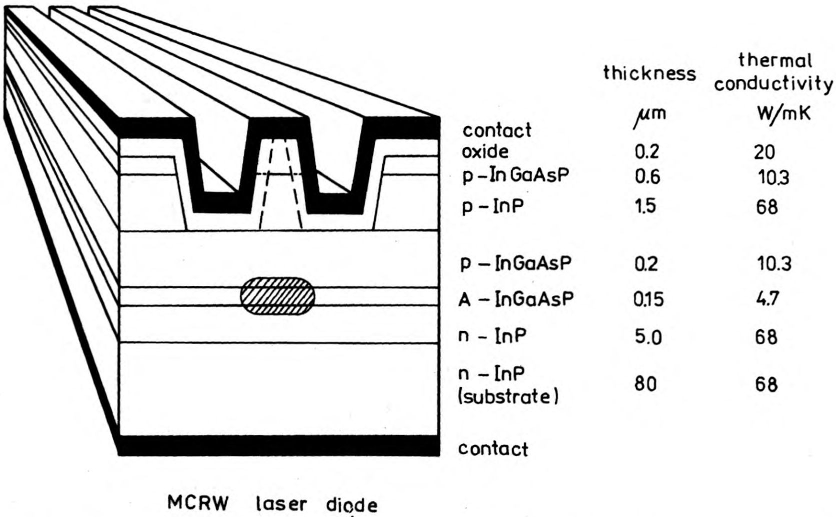


Fig. 1. Schematic drawing of the (InGa) (AsP)/InP metal-clad ridge-waveguide laser diode

In the work [9], the increase in an active layer temperature in the RW laser diode was determined by measuring the temperature-dependent voltage drop at the *p-n* junction at a fixed current [10], [11]. For the laser diodes under consideration, the temperature rise versus the drive current appeared to be nearly linear [9], therefore the Joule heating has not been taken into account. Its yield of heat generation process seems to be rather low.

Two heat sources connected with the radiative transfer of spontaneous radiation energy have been also neglected mainly because of their yields being an order of magnitude lower than that of the main heat source, and also because of different positions of these sources. One of them is placed very close to the copper heat sink of a high thermal conductivity (i.e., within the cap (InGa) (AsP) layer), whereas the second one is situated very far from the active area (i.e., the semiconductor/bottom contact interface), and the heat flux generated there is to a considerable extent conducted by the metallization and the bonding wire.

In the analog electrical model, the active area is divided into 201 identical segments and spreading of the current (i.e., of the heat flux) generated in each segment is considered separately. A resultant potential (i.e., temperature) distribution is obtained using the superposition rule. In the calculations the multilayer structure of the laser, the thermal resistance of contact and oxide layers, the spreading thermal resistance of a heat sink and the radiative transfer of the spontaneous emission are taken into account.

Spreading of the current generated in one segment of the active area is schematically shown in Fig. 2. The current is divided into two parts: one flowing throug the ridge, and the other which flows through the substrate. The corresponding thermal resistances denoted in this figure form a simple current circuit shown in Fig. 3.

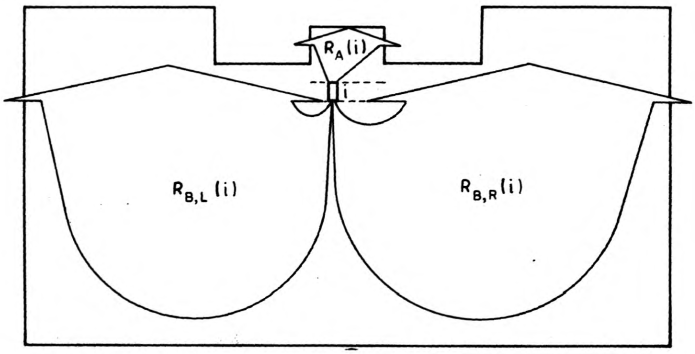


Fig. 2. Spreading of the current generated in the *i*-th segment of the active area in the analog electrical model of the metal-clad ridge-waveguide laser diode

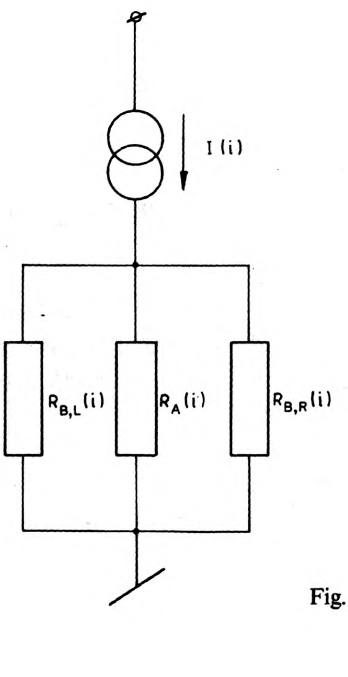


Fig. 3. Equivalent electrical circuit of the current spreading shown in Fig. 2

3. Results

Main results of the theoretical model in form of plots of the above mentioned position-dependent thermal resistances are presented in the next two figures. Nominal set of the parameters used in the calculations is given in Tab. 1.

Table 1. Nominal set of the parameters used in the calculations

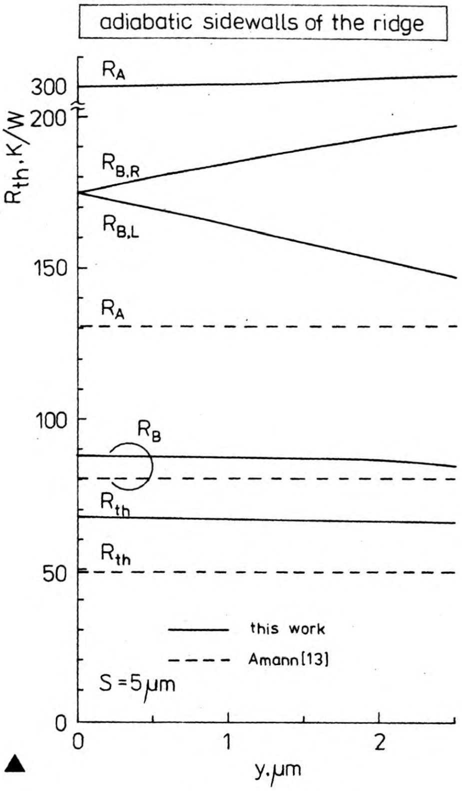
Parameter	Denotation	Value	Unit
Chip length	L	200	µm
Chip width	W	400	µm
Stripe width	S	5	µm
Groove width	C	15	µm
Thicknesses of the layers:			
– *n*-type InP	d_n	85	µm
– active $Ga_{0.29}$ $In_{0.72}$ $As_{0.62}$ $P_{0.38}$	d_A	0.15	µm
– etch-stopping $Ga_{0.09}$ $In_{0.91}$ $As_{0.20}$ $P_{0.80}$	d_{es}	0.3	µm
– ridge *p*-type InP	d_p	1.5	µm
– cap $Ga_{0.28}$ $In_{0.72}$ $As_{0.62}$ $P_{0.38}$	d_c	0.6	µm
– oxide SiO_2	d_o	0.2	µm
– solder In	d_{In}	10	µm

In the case of adiabatic sidewalls of the ridge (Fig. 4), i.e., for a very high thermal resistance of the oxide layer covering these walls, the ridge thermal resistance R_A is quite high and nearly constant. Heat abstraction through the substrate (described by the thermal resistance R_B) is much more efficient.

The same plots for the more realistic assumption of isothermal sidewalls are shown in Fig. 5. It appears, however, that, for both the cases, the heat abstraction through the ridge plays only a supplementary role in the whole heat-sinking process in the MCRW laser diode, and that about 60%–70% of the heat flux generated in the active region flows through the substrate. This result is in a very close agreement with that published by PIPREK and NUERNBERG [12] who analysed the heat spreading in an RW (InGa) (AsP)/InP laser using a special numerical procedure prepared by the University of California at San Diego. It was also confirmed by an experiment [9].

The results of an approximate AMANN's model [13] shown in both the figures are not consistent with our ones. The discrepancy is caused by numerous (and not always justified) assumptions taken by Amann. Nevertheless, he also justly pointed out that the major contribution to the heat dissipation in a typical MCRW laser diode was connected with the heat path approaching the heat sink in the regions beyond the ridge.

Theoretical values of composite thermal resistances R_A and R_B (cf. Fig. 3) of the nominal laser structure (see Tab. 1) are compared with the experimental ones [9] in Tab. 2. As one can see, these values are very close to one another confirming the



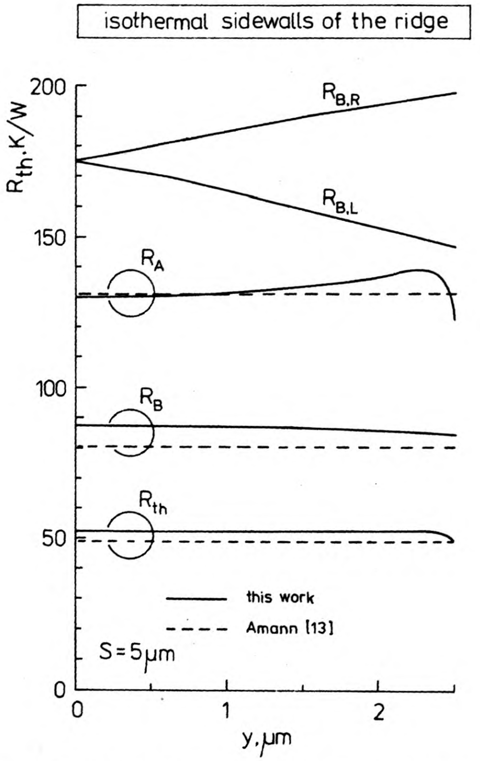


Fig. 4. Position-dependent thermal resistances in the case of adiabatic sidewalls of the ridge of the standard MCRW (InGa) (AsP)/InP laser diode (see Table 1)

Fig. 5. Position-dependent thermal resistances in the case of isothermal sidewalls of the ridge of the standard MCRW (InGa) (AsP)/InP laser diode (see Table 1)

Table 2. Comparison of theoretical and experimental values of the composite thermal resistances R_A and R_B of the nominal MCRW (InGa) (AsP)/InP laser structure

Thermal resistance		Theory		Experiment [9]
		Structure		
Denotation	Unit	with oxide layer on vertical walls	without oxide layer on vertical walls	
R_A	K/W	133	185	170–220
R_B	K/W	86.5	86.5	80–85
R_{TH}	K/W	52	59	55–61

validity of the model. The relatively high experimental value of the R_A thermal resistance may be due either to the presence of the oxide layer on vertical walls of the ridge or to the formation of intermetallic compounds between the gold contact and the In solder.

The model validity is also confirmed by comparison (in Tab. 3) of theoretical (for the structures with an oxide layer on vertical walls of the ridge) and experimental [9] values of the thermal resistances R_{TH} of various laser structures: common, half-soldered and with channel free of solder.

Table 3. Comparison of theoretical and experimental [9] values of thermal resistances R_{TH} of the MCRW lasers

	Thermal resistance			
	Cu heat sink		Si heat sink	
Structure	Theory	Experiment	Theory	Experiment
Ordinary	59	55–61	68	65–75
Half-soldered	116	–	144	156–164
Solder-free channel	83	–	91	80–82

4. Conclusions

Theoretical analysis of heat-flux spreading in the metal-clad ridge-waveguide (InGa) (AsP)/InP laser diodes is presented in this work. Theoretical model is based on the analog electrical method. Its results are compared with the experimental ones.

In appears that in a typical MCRW (InGa) (AsP)/InP laser diode the heat abstraction through the ridge only plays a supplementary role in the whole heat-sinking process and that 60%–70% of the heat flux generated in its active area flows through the substrate.

Theoretical values of the thermal resistances of the standard ($S = 5$ μm) metal-clad ridge-waveguide (InGa) (AsP)/InP laser diode are equal to 59 K/W and 68 K/W for the copper and the silicon submounts, respectively. These values agree very well with the experimental data.

The above theoretical analysis makes it possible to carry out thermal optimalization of the laser structure.

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Теоретическое исследование процесса распределения тепла в лазерах с Н-образным волноводом покрытым металлом (типа MCRW)

В работе представлены результаты теоретического анализа процесса распределения тепла в лазерах типа MCRW (metal-clad ridge-waveguide lasers). т. е. в лазерах с Н-образным волноводом покрытым металлом. Оказалось, что отвод тепла Н-образным играет в этом процессе лишь дополнительную поль и 60–70% струи тепла генеруемого в действующей области проходит через основание. Для типичной конструкции лазера MCRW шириной полосатой действующей области $S = 5$ μm теоретическое значение теплового сопротивления есть 59 K/W (для лазера прикрепленного к медной основе) и 68 K/W (в случае кремневой основы). Эти значения хорошо согласуются с экспериментальными данными.